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Background, 1

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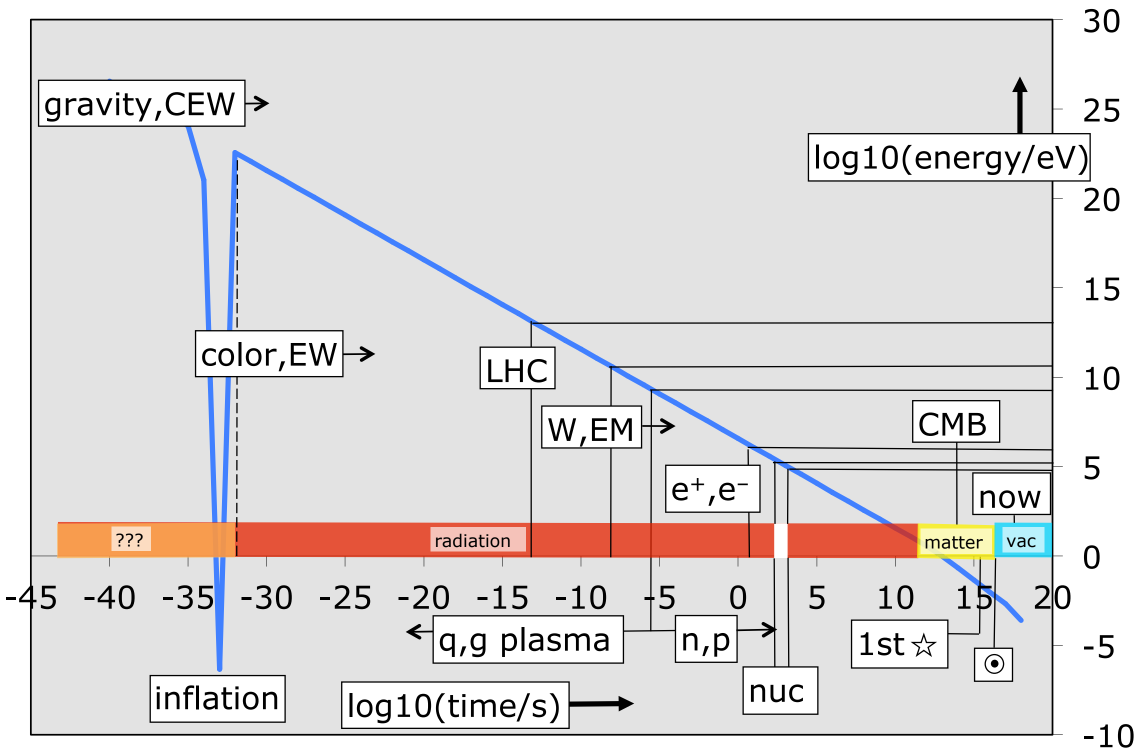
This course deals with the structure of matter at its extreme length scales: cosmological on the large end (on the order of 10^{26} m), sub-nuclear on the small (less than 10^{-19} m). It also deals with the now firmly established realization that the organization of matter on these two phenomenally different scales is actually intimately connected. This course is about science in its most alive and vibrant state: what we think we know about the big and small of the universe changes virtually daily. Satellite observatories and ground-based particle accelerators make what was formerly "common knowledge" obsolete at a rapid pace. That's one reason the course is so cool. Another is the kind of questions this science is about: it deals with the most fundamental questions of all—where did we come from and where are we going?

It is useful to begin with "a brief history of time" (to borrow the title of Steven Hawking's famous best-seller: Bantam, 1998, ISBN 978-0553380163). The figure below depicts some important moments in the putative history of the universe. The axes of the graph are $\log_{10}$(time/s) and $\log_{10}$(energy/eV). Thus a change of one unit on either axis corresponds to a change of a factor of ten in the corresponding quantity as it is usually measured. Logarithms are used because of the enormous ranges we will be discussing.



Some of what is shown is well established, but much is still highly conjectural. In the discussion that follows, I will assign to each idea a "believability index" (**BI**)—with **5** being the most believable (based on almost irrefutable evidence) and **1**, the least (at this moment, at least, largely wishful thinking). <u>This is a highly subjective activity and itself probably merits a **BI=1**, so beware</u>.

1. One well established aspect of the current universe (the point *now* in the figure), is that we are bathed in a sea of photons, coming to us from all directions almost exactly

identically, and with a frequency spectrum that is described to high accuracy and precision by *blackbody radiation* **(BI=5)**. A blackbody spectrum is characterized by a single parameter: temperature. The temperature of this cosmic microwave background (CMB) radiation is 2.725±0.0001 K (an uncertainty of only about one part in 3000). The average energy of a photon in the CMB is only about $6x10^{-4}$ eV, far too small to excite any neutral atom electronic state. So the CMB cannot be explained by any photon-atom interaction at the present time. Such interactions would require the average photon energy of the CMB to be about 1000 times greater than at present.

2. Blackbody radiation cools as time goes on in an expanding universe, so the requisite temperature could have occurred earlier (*CMB* in the figure) provided the *universe is expanding*. In fact, there are several other compelling reasons for inferring that this is so **(BI=5)**.

3. The thick blue curve in the figure above is the average photon energy in a blackbody radiation field that is cooling because of expansion and whose current temperature is 2.725 K. The rate of expansion (and hence cooling) is calculated using a cosmological model based on *general relativity* **(BI=4)**.
4. The rate depends on the mass-energy content of the universe at any moment and varies from epoch-to-epoch (indicated by the horizontal colored bars in the figure). This model predicts many interesting phenomena that are in very good agreement with observation; its credibility is currently held in high regard. Extrapolating from observed cosmic values of atomic matter, radiation, and other forms of energy, the model implies that about 13.77(±0.07)$x10^{9}$ years (= 4.34(±0.02)$x10^{17}$ s) ago, the universe was much denser and much hotter than at present—so dense and hot that *atoms could not have existed* **(BI=4)**, *nor nuclei* **(BI=4)**, nor, for that matter, *even the protons and neutrons* from which nuclei are made **(BI=4)**.
5. The hot early universe model implies that for most of the *logarithmic* history shown in the figure (the *radiation* epoch), blackbody energy dominated all other forms of mass/energy, and its temperature dictated what events could and could not occur. The blue curve in the figure connects the earliest and latest moments of the expanding universe scenario and makes plausible the idea that *matter on the smallest and largest scales is intimately related*. At energies of interaction below about 10 on the log(ENERGY/eV) scale (i.e., 10^{10} eV), there are excellent, empirically based reasons to distinguish four *fundamental forces*—electromagnetism, the strong and weak nuclear forces, and gravity **(BI=5)**.
6. The Large Hadron Collider (*LHC*) is a kind of "time machine," allowing us to probe the state of matter at about *TIME* = –13. At the energy of the LHC matter probably consists of a small number of *fundamental particles*—six kinds of leptons (including the electron and the electron neutrino), six kinds of quarks (from which such things as the proton and neutron are made), plus a small number of "exchange particles" (including the photon) that are responsible for conveying the fundamental forces from particle-to-particle **(BI=4)**. This is the earliest time in the history of the universe for which we currently have direct observational evidence. "Physics type stories" you may have heard about earlier times, at this moment, should be taken with a large grain of salt **(BI=1)**. But we'll visit some these later.
7. The clock of the universe is arbitrarily set to 0 s at the moment of our greatest physical ignorance; this is *TIME* = $-\infty$ in the units used in the figure. The first even vaguely physics-like idea pops in about 10^{-43} s (at *TIME* = –43) **(BI=1)**.
8. Between the LHC time and now other fairly certain **(BI=3** to **BI=4)** events must have occurred. These include: (a) the coalescence of quarks (and the color force carrier "gluons") into neutrons and protons (the *q,g plasma* event near *TIME* = –5); (b) the annihilation of free positrons and electrons into photons (e^+,e^- near *TIME* = 1); (c) the

coalescence of free neutrons and protons into (some) atomic nuclei (*nuc* near *TIME* = 2); and (d) the coalescence of free protons and electrons into neutral atoms and the freeing of the cosmic microwave blackbody background (*CMB* near *TIME* = 13).

9. The CMB release point is about 400,000 years after the Big Bang. Earlier than that, at about 10,000 years (near *TIME* = 11), radiation would have ceased being the dominant form of energy in the universe and would have been replaced by massive particles (*matter* epoch) **(BI=3)**.
10. The universe would have been too hot at that point for gravity to assemble local clumps of matter—i.e., no stars, no planets, no galaxies. The first stars, it is speculated **(BI=3)**, did not appear until a few hundred million years (*1st☆* near *TIME* = 16).
11. The first galaxies might have formed “shortly” after (older galaxies such as the Milky Way are at least 13 billion years old) **(BI=3)**.
12. Curiously, at about the same time as the formation of our solar system (⊙ [i.e., Sun]) something new seems to have happened: massive particles no longer dominated the universe’s energy. Currently, it looks as if the energy of the universe is mostly an as yet unobserved form, sometimes called “dark energy” (dark, because we don’t directly see it) **(BI=2)**.
13. Dark energy appears to be causing the expansion of the universe to accelerate. During the succeeding epoch the universe will presumably expand ever faster—it seems—leading eventually to … who knows **(BI=1)**?

This very quick introduction requires much further discussion, which is what this course is about. The point to remember for now, however, is that the present condition of the cosmos is intimately related to the past, and that was dominated by the physics of elementary particles. Cool, no?